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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 369

EFFECT OF ORIFICE LENGTH-DIAMETER RATIO ON THE COEFFICIENT
OF DISCHARGE OF FUEL-INJECTION NOZZLES

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Summary

The variation of the coefficient of discharge with the length-diameter ratio of the orifice was determined for nozzles having single orifices 0.008 and 0.020 inch in diameter. Ratios from 0.5 to 10 were investigated at injection pressures from 500 to 5,000 pounds per square inch.

The tests showed that, within the error of the observation, the coefficients were the same whether the nozzles were assembled at the end of a constant diameter tube or in an automatic injection valve having a plain stem. For these assemblies the coefficient was constant between the ratios of 1 and 4. For ratios greater than 4 the coefficient gradually decreased as a result of friction losses.

The coefficients of the nozzles when assembled in an injection valve having a helically-grooved stem were lower than when assembled with a plain stem. There was but little variation in the value of the coefficient with the ratio for the 0.020-inch orifice. The coefficient for the 0.008-inch orifice, however, varied considerably with the ratio, showing some irregularities between the ratios of 0.5 and 4.

Introduction

Investigations on the coefficient of discharge of small, round orifices have been conducted by Joachim (Reference 1), by Gelalles (Reference 2), and by Bird (Reference 3). Joachim and Gelalles used nozzles having single orifices of diameters varying from 0.008 to 0.040 inch. Several geometrical shapes of entering passage and several orifice length-diameter ratios were tested. Injection pressures up to 8000 pounds per square inch were used. The coefficient of discharge was found to be the same for the length-diameter ratios between 1 and 3. The results obtained when the geometrical shape of the entering edge of the orifice was made to approach that of a Venturi nozzle were similar to the results obtained with nozzles of larger scale but of the same shape. Irregular results were obtained, however, with orifices having a sharp leading edge.

Bird investigated the effect of length-diameter ratio on the coefficient of discharge of a 0.013-inch diameter orifice. He varied the ratio from 0.4 to 10, and the injection pressure from 1,000 to 5,000 pounds per square inch. A curve with certain sharp irregularities was obtained when the coefficient was plotted against the length-diameter ratio. The lower range of the Reynolds Number of the flow, combined with a nozzle design giving a high contraction coefficient, were, apparently, responsible for these irregularities in the coefficient of discharge curve.

The purpose of the present investigation was to determine the variation of the coefficient of discharge of small, round orifices with length-diameter ratios of a more extended range than was tested previously at this laboratory by Gelalles. (Reference 2) Two nozzles having single orifices 0.008 and 0.020 inch in diameter were tested when assembled at the end of a constant-diameter tube and in an injection valve with either a plain or a helically-grooved stem.

The investigation was conducted at the Langley Memorial Aeronautical Laboratory at Langley Field, Virginia. The work was conducted simultaneously with an investigation on the effect of length-diameter ratio of the orifice on fuel spray characteristics, the results of which are to be published as a separate report.

Apparatus and Methods

The apparatus used in determining the coefficients of discharge was the same as that employed in the previous investigations at this laboratory. A description of this apparatus, its operation, and the possible experimental errors are given in Reference 2. The method used in determining the coefficient of discharge of the orifices was to time the flow of a known volume of fuel oil through the orifice and then to determine the coefficient as the ratio of the actual to the ideal rate of flow.

The equation from which the coefficient C was computed is

$$C = \frac{Q}{a \, t \, \sqrt{2 \, g \, \frac{(P_1 - P_2)}{\rho}}} \quad (1)$$

Q is volume of the fuel oil discharged.

a is area of the orifice.

t is time of discharge.

g is gravitational acceleration.

P_1 is injection pressure.

P_2 is chamber pressure.

ρ is density of the fuel oil.

Owing to the difficulties of machining such comparatively large lengths for the small orifices tested, the diameter of the throat was not uniform throughout. As shown by Table I, which gives the micrometer readings of the outside openings after each successive grinding off the end of the nozzle to the proper ratio, the variation with the 0.008-inch orifice was 7.3 per cent, and with the 0.020-inch about 2.9 per cent. The maximum variation between any two consecutive ratios tested was 3.5 per cent with the 0.008-inch and 2.1 per cent with the 0.020-inch orifice. The diameter at the exit of the throat, as measured for each ratio, was used as the orifice diameter for calculating the coefficient.

Tests were made with the nozzles mounted at the end of a tube with a constant diameter (Fig. 1C), with the nozzle assem-

bled in an injection valve having a plain stem (Fig. 1A) and one having a helically-grooved stem (Fig. 1B). Cross sections of the nozzle assemblies are shown in Figure 1. In the accompanying table the size of the orifices and the length-diameter ratios tested are given. The orifice sizes tested were 0.008 and 0.020 inch in diameter at the length-diameter ratios of 0.5, 1.0, 2.0, 3.0, 4.0, 6.0, 8.0, and 10.0. The hydraulic injection pressure was varied from 500 to 5,000 pounds per square inch. Air at atmospheric pressure was used in the discharge chamber. The fuel was a high-grade Diesel oil with a specific gravity of 0.86 and an absolute viscosity of 0.048 poises (45 seconds Saybolt Universal) at 80° degrees Fahrenheit.

Results and Discussion

Figures 2 and 3 give the effect of the length-diameter ratio on the coefficient of discharge for the orifices with the nozzles mounted at the end of a tube of constant inside diameter (Assembly C, Fig. 1). Within the experimental error, identical results were obtained when the nozzles were assembled in the injection valve with the plain stem (Assembly A, Fig. 1). The data with the nozzle at the end of a constant diameter tube given in this note, therefore, may also be taken to represent data with an injection valve having a plain stem and the same nozzle. There was a slight decrease in the value of the coefficient for the 0.020-inch orifice as the length-diameter ratio

was decreased from 2 to 0.5. Between the ratios of 1 and 4, the variation of the coefficient from its maximum value was small with both orifices. The coefficient gradually decreased as the length-diameter ratio of the orifices was further increased.

In previous investigations at this laboratory with nozzles having the same geometrical shape but with an orifice diameter of 0.014 inch, the coefficient was found to have the constant value of 0.94 for ratios from 1 to 3 and injection pressures from 1,000 to 4,000 pounds per square inch. (Reference 2.) This coefficient is slightly higher than that obtained with the orifices of these tests at the same conditions, but the deviation is close to the experimental error of 2 per cent.

The decrease in the value of the coefficient for length-diameter ratios greater than 4 is due to the increased friction losses, which become of appreciable magnitude as the orifice length is increased further. In Figures 4 and 5 the curves of Figures 2 and 3 are shown corrected for friction losses beyond the length-diameter ratio of 3. In Figures 6 and 7 are given the coefficients for the 0.008-inch orifice, uncorrected and corrected for losses, respectively, when plotted against the injection pressures. To determine the friction losses the usual equation for pressure losses in pipes is used, i.e.,

$$P = f L V^2 \frac{\rho}{2 d g} \quad (2)$$

where

P is pressure head loss.

L is pipe length.

V is flow velocity.

ρ is density of the liquid.

d is diameter of pipe.

f is coefficient of friction.

The friction coefficient f is a function of Reynolds Number $\frac{(V d)}{\nu}$, in which ν is the kinematic viscosity of the liquid.

The value of f has been determined experimentally for a large range of Reynolds Number. Hopf (Reference 4) has found that for Reynolds Numbers greater than 2,300, i.e., turbulent flow range, f is expressed by the equation

$$f = 0.00714 + 0.6104 \frac{(V d)}{\nu}^{-0.35}$$

A correction for friction head loss was applied to equation (1) as follows:

From equation (1)

$$C = \frac{Q}{a + \sqrt{2 g \frac{(P_1 - P_2)}{\rho}}} = \frac{K}{\sqrt{\Delta P}}$$

in which

$$\Delta P = P_1 - P_2 \quad \text{and} \quad K = \frac{Q}{a \, t \sqrt{\frac{2g}{\rho}}} \quad \checkmark$$

From equation (2) the pressure head loss P is obtained and the corrected coefficient of discharge is

$$C' = \frac{K}{\sqrt{\Delta P - P}} \quad \times$$

or

$$C' = C \frac{\sqrt{\Delta P}}{\sqrt{\Delta P - P}} \quad \checkmark \quad (3)$$

Examination of Figures 4, 5, and 7, giving the corrected coefficients, shows that, except for the length-diameter ratio of 10 with the 0.008-inch diameter orifice, the coefficient of discharge is the same for all ratios greater than 1, within the error of the observation (about 2 per cent). No correction was applied for the lengths of ratios less than 3, for these lengths come within the jet contraction region at which the magnitude of the losses is unknown.

No definite explanation can be given for the lower corrected coefficient for the length-diameter ratio of 10 with the 0.008-inch orifice. Either one of two causes is possible. As seen from Table I, the outside opening of the orifice at the ratio of 10 was disproportionately larger than at the ratio of 8. It is possible, then, that the issuing jet did not completely fill the outside opening of the orifice with the tests at length-diameter ratios of 10. A small difference between the orifice

diameter used in the calculations and the actual jet diameter at the outside opening would affect the value of the coefficient considerably because the coefficient varies inversely as the square of the jet diameter. The other possible cause is that there was another jet contraction at that ratio. The spiral motion given to the jet as it passes from the large diameter of the tube to the small diameter of the orifice is known to persist even after the jet issues from the orifice. It is probable that the jet again contracted at the length corresponding to the ratio of 10 after its first contraction and re-expansion near the inner edge of the orifice. Bird's curve of coefficient against length-diameter ratio also shows a second depression at the ratio of 7.5 (Reference 3).

In Figure 8 the relation of the coefficient and the hydraulic injection pressure to the Reynolds Number of flow is given. The kinematic viscosity of the fuel oil was obtained from data given in a previous publication of the Committee on the same oil. (Reference 5). These curves indicate that the flow becomes definitely turbulent (Reference 2, Appendix) at pressures above 1,000 pounds per square inch even with the smaller orifice tested. The smaller coefficients obtained at pressures below 1,000 pounds per square inch with the 0.008-inch orifice (~~Figures~~ 6 and 7) indicate a flow in the semi-turbulent region. The coefficients for the 0.020-inch orifice at 500 pounds per square inch injection pressure were the same

as at 1,000 pounds per square inch pressure. (Figs. 3 and 5). This fact, together with the curves given in Figure 8, indicates that the flow with this orifice is well within the turbulent region.

Centrifugal sprays.— In Figure 9 are shown the results obtained with the nozzles assembled in the injection valve with the helically-grooved stem (Assembly B, Fig. 1). The variation in the value of the coefficient was small for the 0.020-inch orifice with changes in either the length-diameter ratio of the orifice or the injection pressure. Sharp irregularities were observed, however, for the 0.008-inch orifice. The irregularities were decidedly greater with the higher injection pressures. In general, the coefficient decreased with the increase of the ratio from 0.5; a minimum was reached at the ratio of about 2, to be followed by a maximum at the ratio of 3 and then to decrease again as the ratio was increased further.

These irregularities are peculiar only to this small orifice. Previous test results with a 0.014~~4~~ and a 0.040~~4~~ inch orifice indicated no such irregularities (Reference 2); curve forms were obtained that were similar to that of the 0.020-inch orifice given in Figure 9. The set of curves obtained with the 0.008-inch orifice are not unlike the curve obtained by Bird with a 0.013-inch orifice (Reference 3), which indicates an initial turbulence of flow and consequent fluctuating coefficient of contraction for both tests.

These apparently anomalous variations in the value of the coefficient with the length-diameter ratio for the smaller orifice can probably be explained by an examination of the type of flow existing within the grooves and the throat of the orifices. In Figure 10 the coefficients of discharge are plotted against the Reynolds Number of the flow through the orifices for the orifices of these tests and of the previous tests. (Reference 2.)^x In Figure 11 the injection pressures are plotted against the Reynolds Number of flow through each groove. Following the explanation given in Reference 2, by Hodgson (Reference 6) and others, the shape of the curves of Figure 10 would indicate the flow through the 0.008-inch orifice to be both in the semi~~x~~turbulent and definitely turbulent region, depending on the length-diameter ratio and on the injection pressure employed. For orifices larger than 0.008 inch, the flow is definitely turbulent, with the exception of pressures below 1,000 pounds per square inch at which the flow is probably within the semi~~x~~turbulent region.

Examining the curves of Figure 11, the value of the Reynolds Number of the flow through the grooves for the 0.008- and 0.014-inch orifices is below 2,000. It is known that the flow is streamline for Reynolds Numbers below 2,000 when round, straight, smooth pipes are used as the path of the liquid. It is not unlikely, however, that the Reynolds Number at which the critical region begins may be much lower for the rectangular

grooves of these tests than for round, straight pipes. The spiral motion given to the liquid and the sharp entrance to and exit from the grooves are known to be not conducive to streamline flow. For spirally-wound tubes the critical region is found to commence at a Reynolds Number as low as 130. (Reference 4) In any event, in approaching the inner edge of the orifice, the flow becomes, if not already turbulent, semi~~x~~turbulent and then turbulent as the liquid enters the orifice. With the 0.008-inch orifice, the flow through the grooves and the subsequent converging to a jet, as seen from the shape of the curves, is in the semi~~x~~turbulent region at which the coefficient is sensibly affected by any small change in the nozzle shape, such as varying the length of the orifice in respect to the diameter. With the larger orifices, the flow becomes definitely turbulent in both the grooves and in the orifice; the losses are a fixed proportion of the pressure head; and the coefficient is insensitive to any changes in the nozzle shape.

Conclusions

Results obtained with a 0.008~~x~~ and a 0.020-inch diameter orifice, when the nozzle was assembled at the end of a constant diameter tube, showed the coefficient to have an average maximum value of about 0.91 for the length-diameter ratios from 1 to 4. For ratios greater than 4 the coefficient gradually decreased as a result of the friction losses which became appreciable with the greater lengths.

Tests with the nozzles assembled in an automatic injection valve, with sufficient stem lift to prevent throttling, gave the same coefficients as those with the nozzles at the end of a straight tube, within the error of the observation.

Lower coefficients were obtained with the nozzles assembled in an injection valve containing a stem with helical grooves. Approximately a constant coefficient was obtained with the 0.020-inch orifice for the range of ratios and injection pressures of these tests. Irregularities were observed, however, in the value of the coefficient for the 0.008-inch orifice. Examination of curves of coefficient of discharge against the Reynolds Number of flow through the grooves and the orifice disclosed the possibility that these irregularities were a reflection of the type of flow existing within the nozzle with the smaller orifice.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 16, 1931.

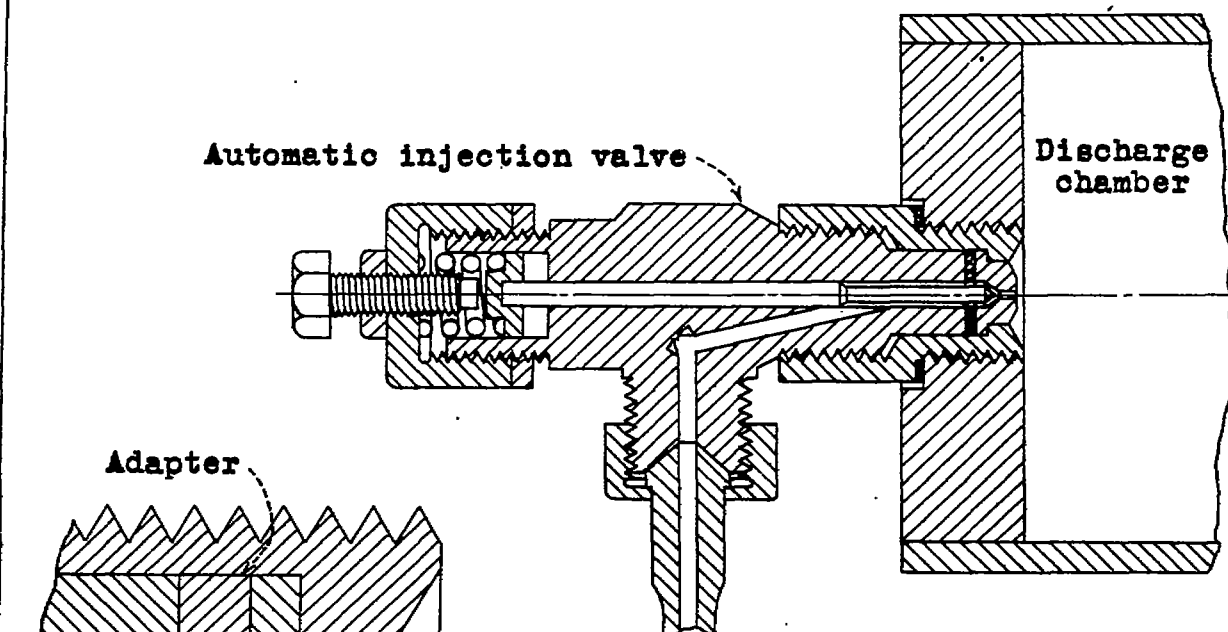
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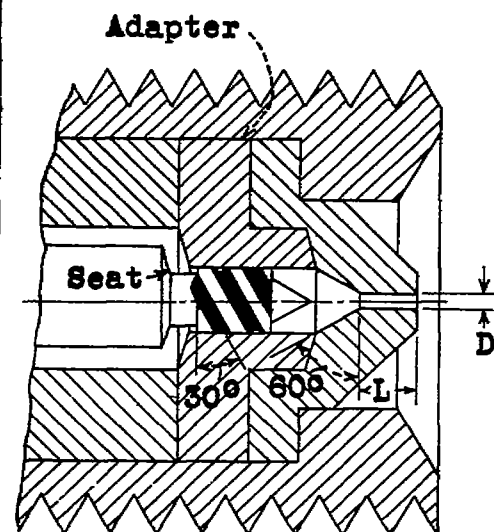
TABLE I

Orifice Diameters

length-diameter ratio	0.008 orifice inches	0.020 orifice inches
10	0.00857	0.02036
8	0.00827	0.02030
6	0.00811	0.01988
4	0.00804	0.01998
3	0.00809	0.02000
2	0.00805	0.01978
1	0.00799	0.02010
$\frac{1}{2}$	0.00815	0.02025



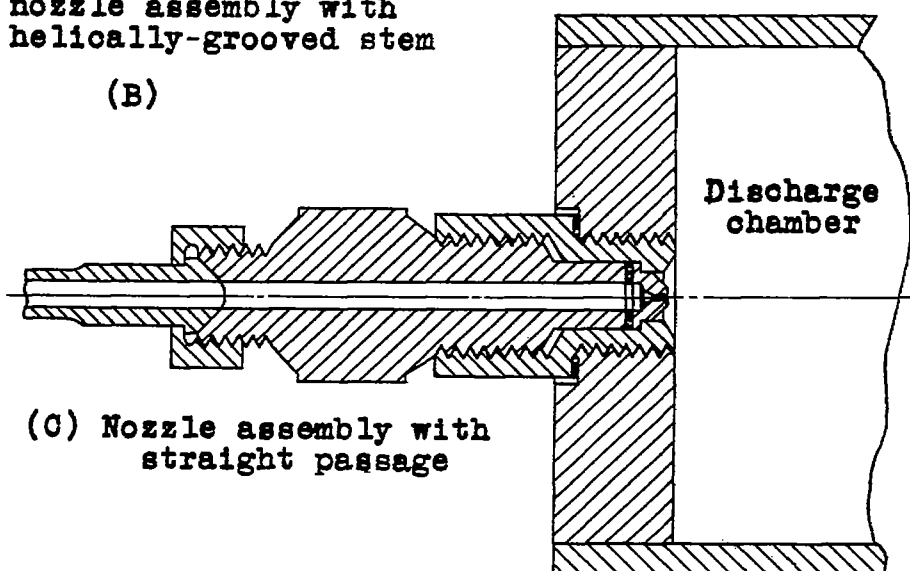
(A) Nozzle assembly with plain stem



Enlarged view of
nozzle assembly with
helically-grooved stem

(B)

Orifice	Length-diameter ratio-L/D
0.008"	0.5, 1, 2, 3, 4, 6, 8 and 10
0.020"	



(C) Nozzle assembly with
straight passage

Fig. 1
Nozzle
assemblies

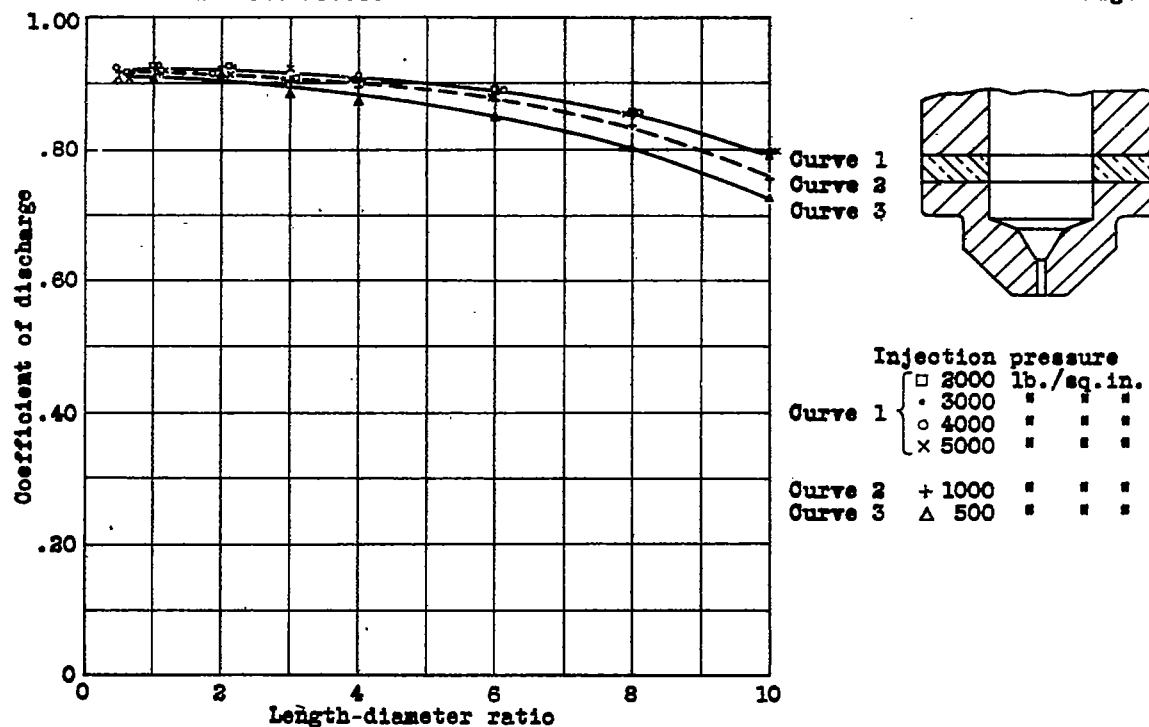


Fig.2 Coefficient of discharge variation with length-diameter ratio of the orifice.
 The 0.008-inch orifice assembled with straight passage. Atmospheric back pressure.

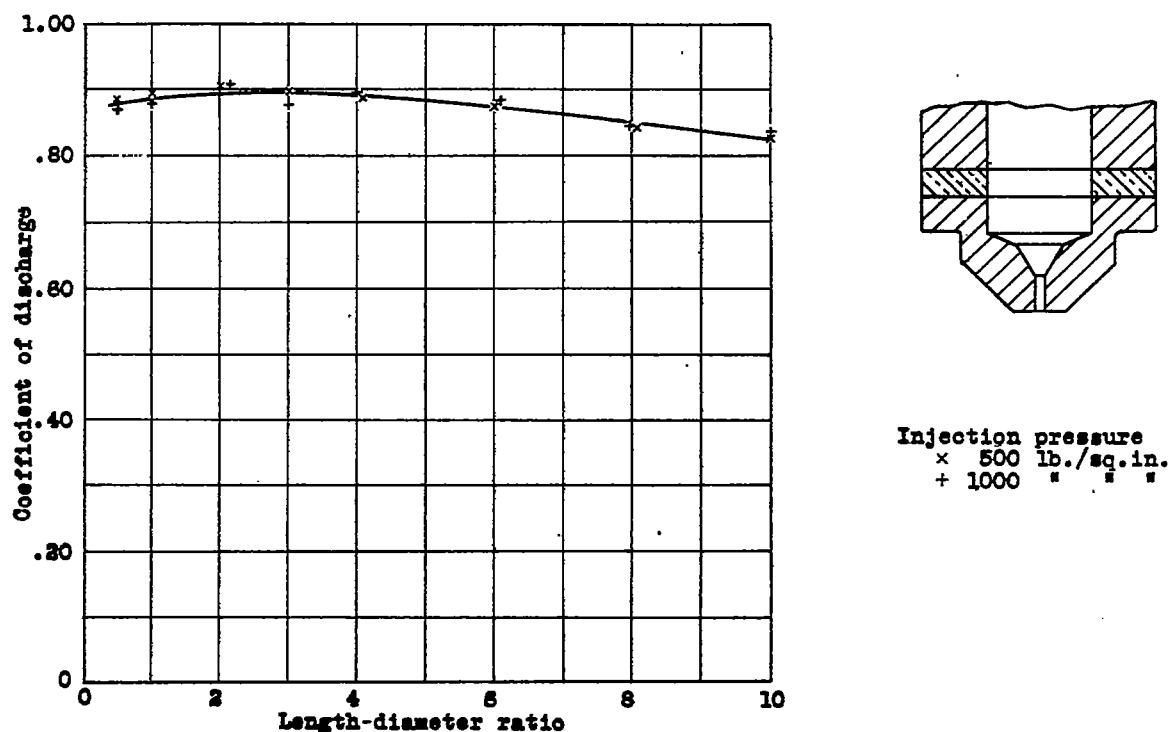


Fig.3 Coefficient of discharge variation with length-diameter ratio of the orifice.
 The 0.020-inch orifice assembled with straight passage. Atmospheric back pressure.

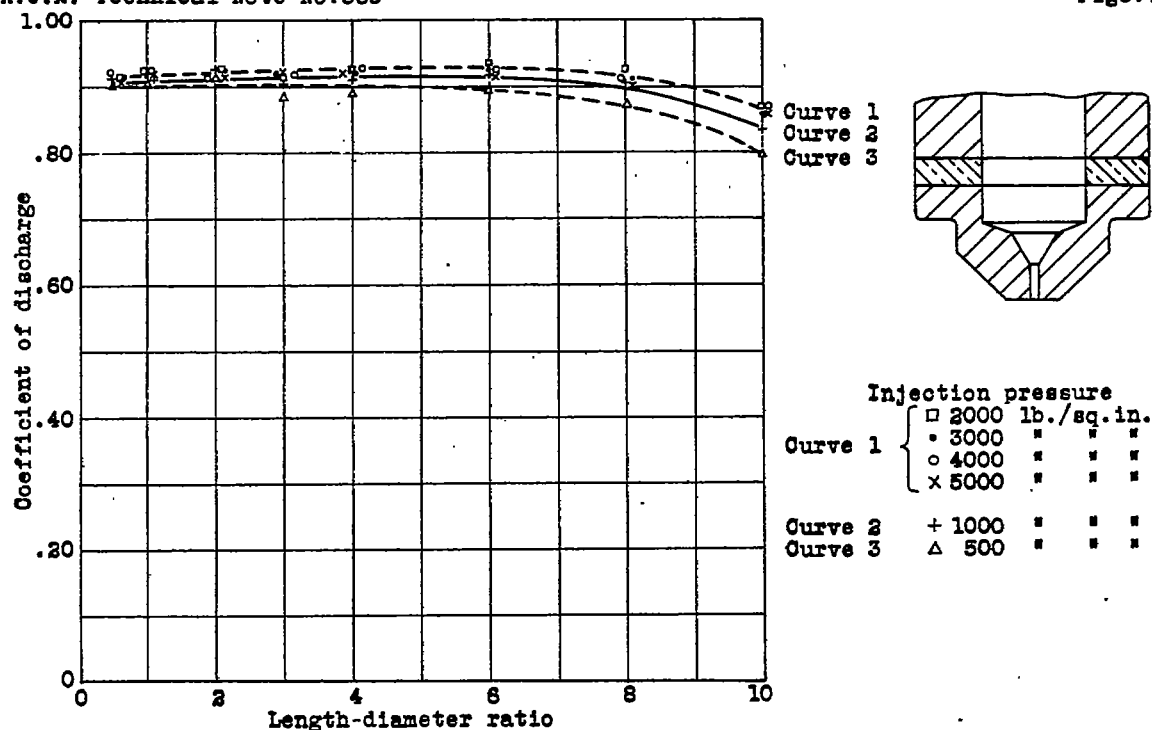


Fig.4 Coefficient of discharge corrected for friction losses. ^{The} 0.008-inch orifice assembled with straight passage. Atmospheric back pressure. Corrected for friction losses above $L/D = 3$.

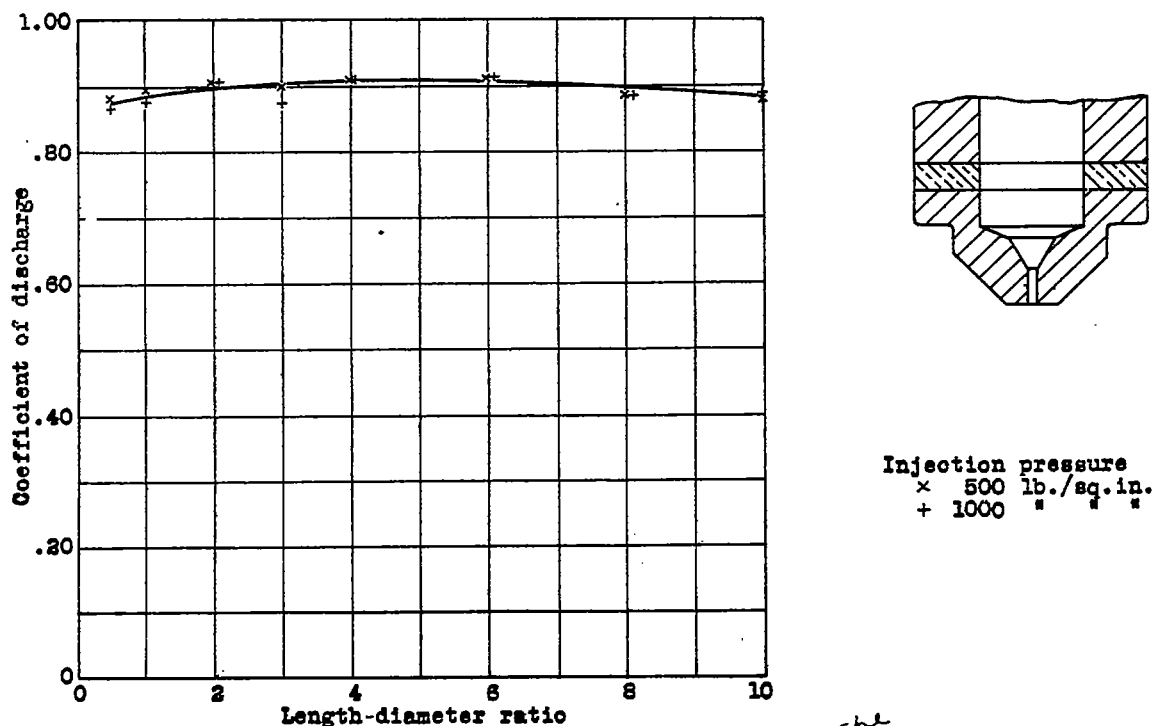
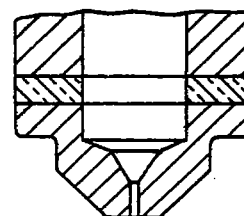
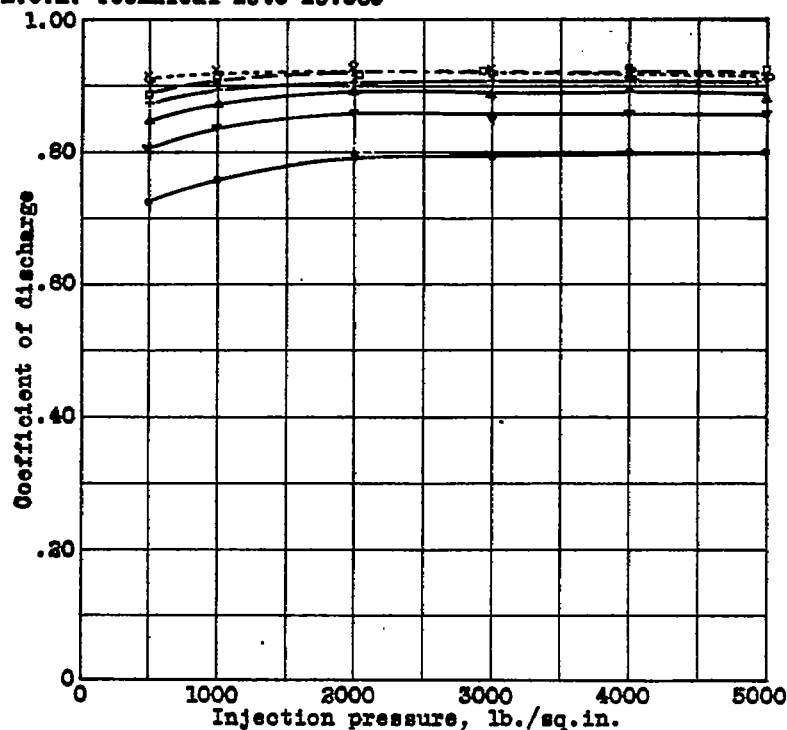
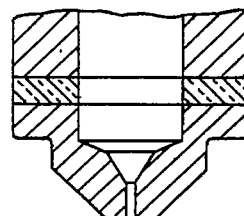
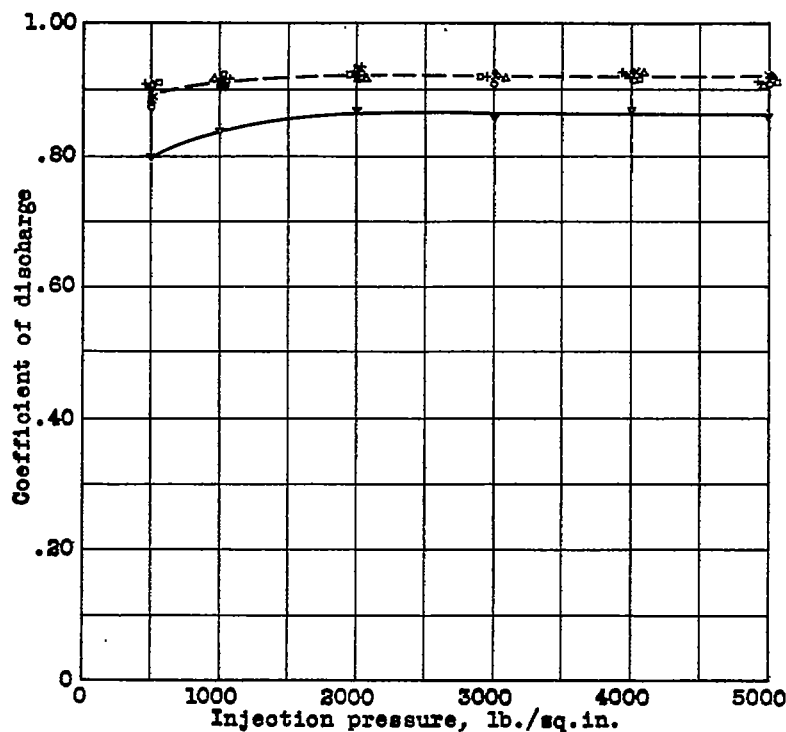


Fig.5 Coefficient of discharge corrected for friction losses. ^{The} 0.020-inch orifice assembled with straight passage. Atmospheric back pressure. Corrected for friction losses above $L/D = 3$.



• $1/2$ length-diameter ratio
 ○ 1
 × 2
 □ 3
 + 4
 △ 6
 ▽ 8
 ◇ 10

Fig. 6 Coefficient of discharge variation with injection pressure. ^{the} 0.008-inch orifice assembled with straight passage. Atmospheric back pressure.



△ $1/2$ length-diameter ratio
 + 1
 □ 2
 △ 3
 × 4
 • 6
 ○ 8
 ▽ 10

Fig. 7 Coefficient of discharge corrected for friction losses. ^{the} 0.008-inch orifice assembled with straight passage. Atmospheric back pressure. Corrected for friction losses above $L/D = 3$.

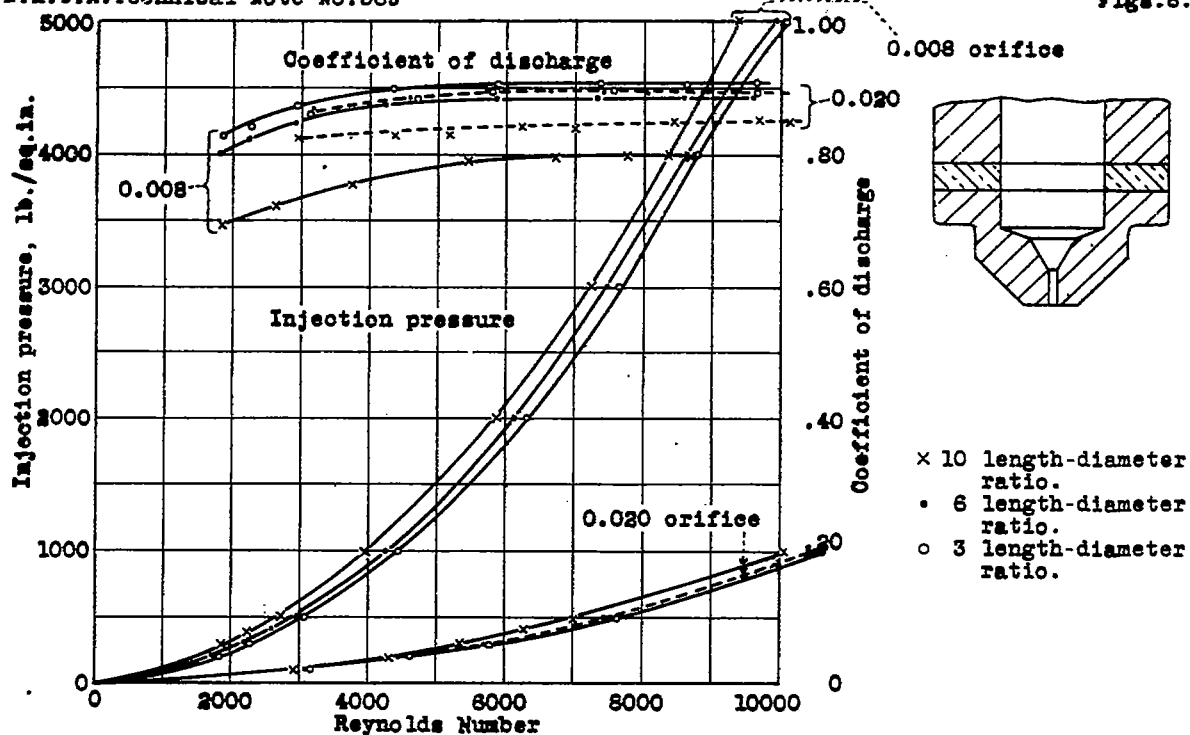


Fig. 8 Reynolds Number of flow corresponding to injection pressure employed. Orifices assembled with straight passage. Atmospheric back pressure.

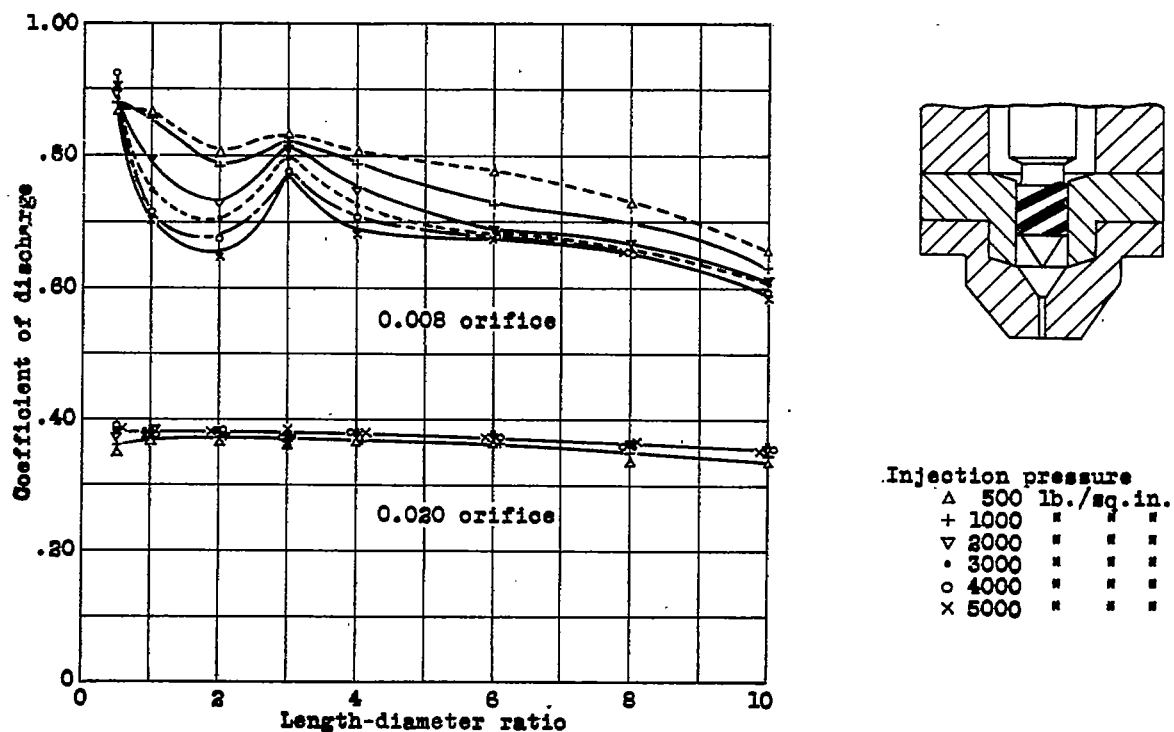
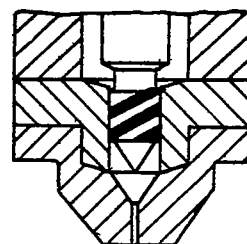
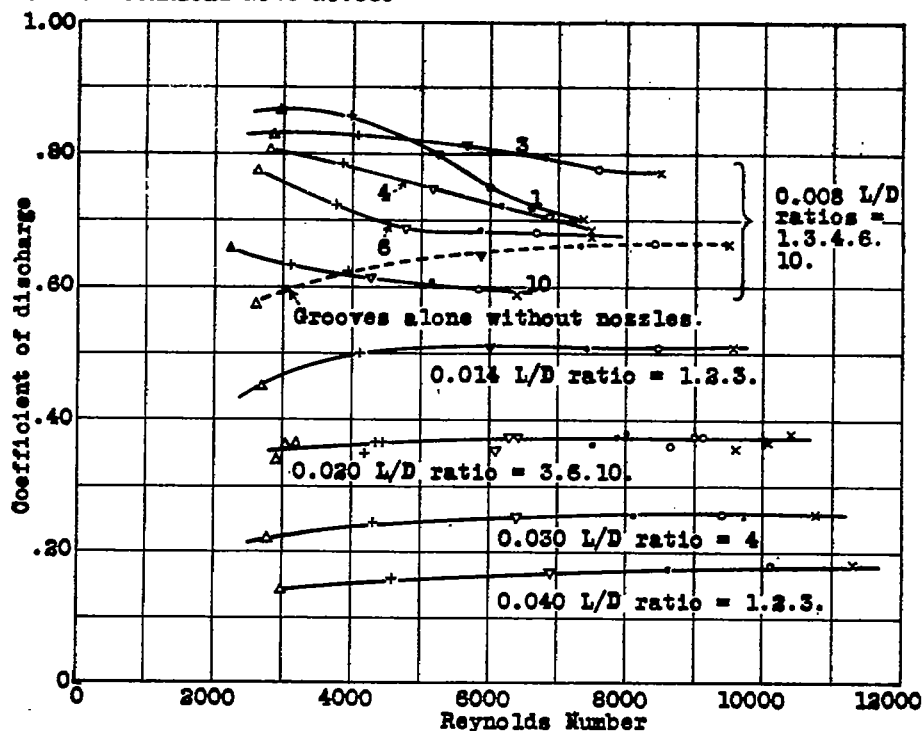
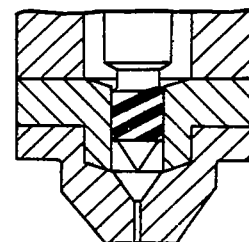
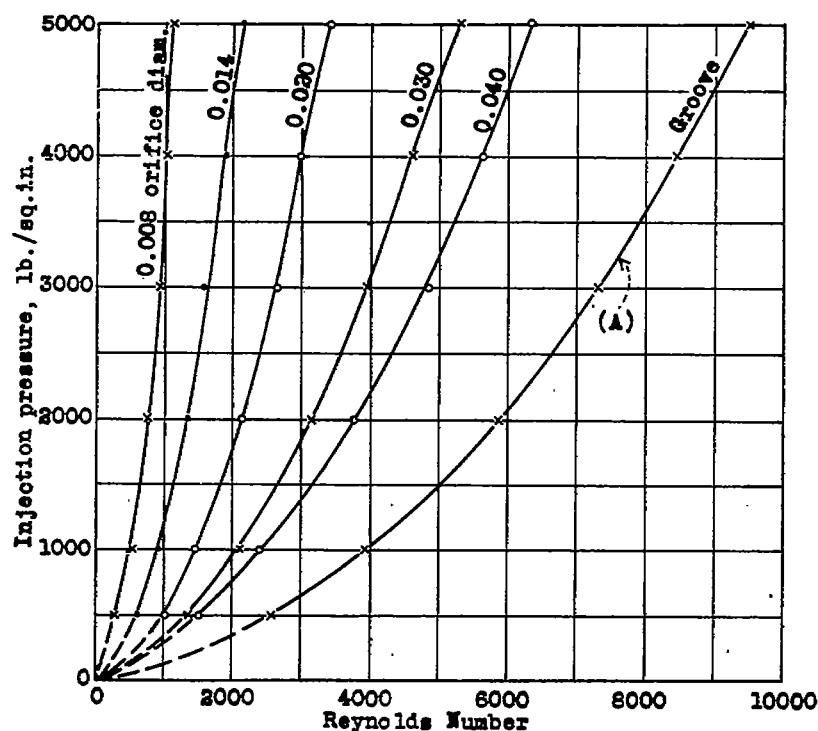


Fig. 9 Coefficient of discharge variation with length-diameter ratio of orifice with a helically-grooved stem in an injection valve. Atmospheric back pressure.



Injection pressure
 Δ 500 lb./sq.in.
 $+$ 1000 " " "
 ∇ 2000 " " "
 \bullet 3000 " " "
 \circ 4000 " " "
 \times 5000 " " "

Fig.10 Reynolds Number of orifice flow with a helically-grooved stem in an injection valve. Atmospheric back pressure.



(A) Discharge directly through the grooves-Helical stem and adapter without nozzles.

Fig.11 Reynolds Number of groove flow with a helically-grooved stem in an injection valve. Length-diameter ratio = 3. Atmospheric back pressure.